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The evolution of robotic surgery: surgical and anaesthetic aspects

H. Ashrafian[1,2], O. Clancy[3], V. Grover[3] and A. Darzi[1,2,*]

[1]Institute of Global Health Innovation, Imperial College London, UK, [2]Department of Surgery and Cancer, Imperial College London, UK and [3]Department of Anaesthesia and Critical Care Medicine, Royal Marsden Hospital, London, UK

*Corresponding author. E-mail: a.darzi@imperial.ac.uk

Abstract

Robotic surgery pushes the frontiers of innovation in healthcare technology towards improved clinical outcomes. We discuss the evolution to five generations of robotic surgical platforms including stereotactic, endoscopic, bioinspired, microbots on the millimetre scale, and the future development of autonomous systems. We examine the challenges, obstacles and limitations of robotic surgery and its future potential including integrated real-time anatomical and immune-histological imaging and data assimilation with improved visualisation, haptic feedback and robot-surgeon interactivity. We consider current evidence, cost-effectiveness and the learning curve in relation to the surgical and anaesthetic journey, and what is required to continue to realise improvements in surgical operative care. The innovative impact of this technology holds the potential to achieve transformative clinical improvements. However, despite over 30 yr of incremental advances it remains formative in its innovative disruption.

Key words: anesthesiology; robotic surgical procedures; surgery, computer-assisted; video-assisted surgery

The birth of robotic surgery took place at a time where there was an increasing demand for greater surgical precision and safer operations, and in an era where surgeons were increasingly adopting minimal invasive surgical (MIS) technologies to enhance their outcomes. The benefits of these minimally invasive approaches (such as laparoscopy and thoracoscopy) included: (i) reduced wound access trauma, (ii) shorter hospital stay, (iii) improved visualisation, (iv) less postoperative wound complications (ranging from wound infections to incisional hernias), and (v) less disfigurement. As such they were designed to offer an equivalence to open surgery with less tissue trauma and speedier discharge that in turn was anticipated to offer (vi) increased cost-efficacy.

The clinical introduction of the Puma 560 in 1985 led to the first surgical robot being applied to perform selective brain biopsies. It was designed to outperform hand biopsies in terms of accuracy and surgical precision. Work with this robot and several others suggested that a digitally programmed tool linked to a surgical cutting device could offer higher levels of operative accuracy when compared with conventional surgical methods. This in-turn led to a paradigm shift in surgical thinking, whereby surgical robots could potentially offer more than "an equivalent-to-open operation with smaller incisions", to one where an operation with a robot would allow a higher level of tissue discrimination, dissection and repair.

Over 30 yr since their introduction, surgical robots occupy an influential role in today's surgical ecology. Their increasing application is derived from the technical benefits of modern robotic platforms, but also from the conceptual science-fiction effect of robotics on modern society where robots represent the pre-eminence of cutting-edge technology.

Technical advantages for the surgeon include: the potential for better visualisation (higher magnification) with stereoscopic

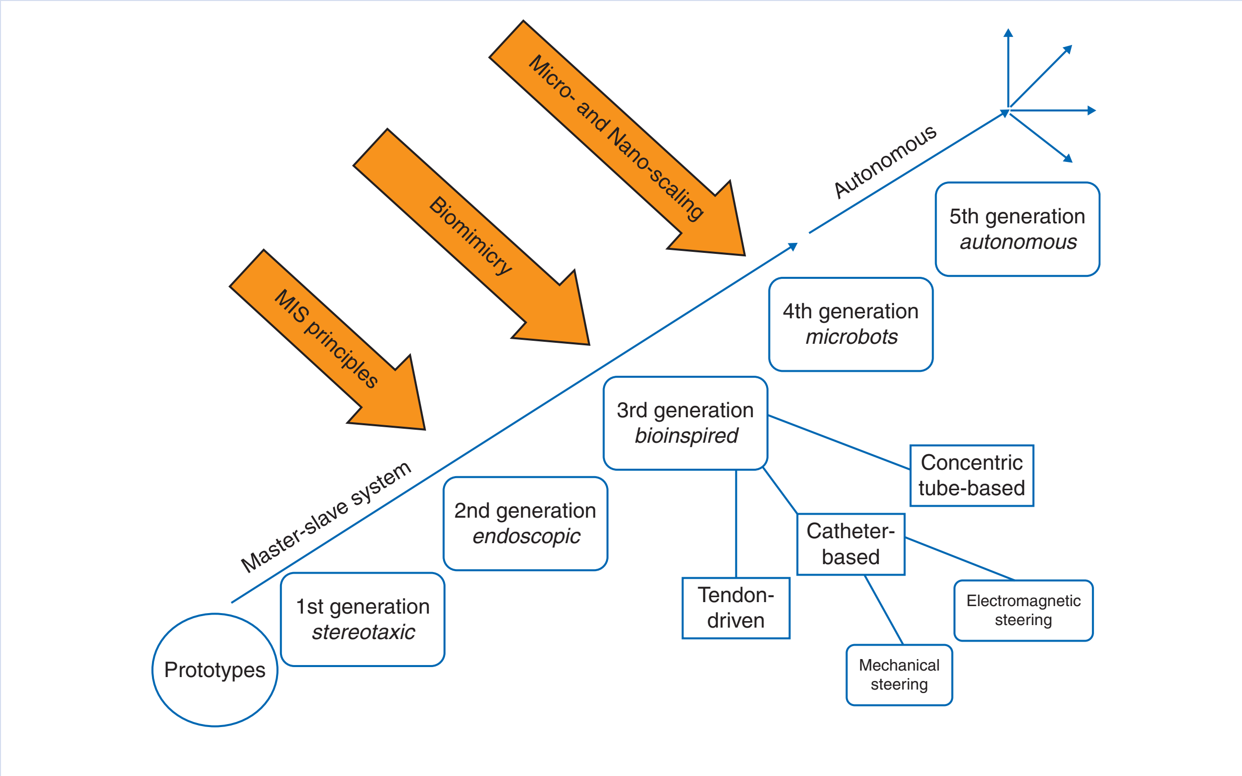

Fig 1 The evolution of five generations of surgical robotics.

views; elimination of hand tremor allowing greater precision; and improved manoeuvring as a result of the "robotic wrist" which in some systems allows up to seven degrees of freedom (angles at which surgeons can use their instruments to operate on target organs). There are improved kinematics where large external movements of the surgical hands can be scaled down and transformed to limited internal movements of the "robotic hands". This in turn improves ergonomics that extend the surgical ability to perform complex technical tasks in a limited space. Here the surgeon is able to work in an ergonomic environment with less stress, achieving higher levels of concentration. The computerized nature of the surgical robot allows integration of real-time and previously recorded data utilisation, so that it could accommodate complex intra-operative factors such as compensating for the beating movement of the heart, making it unnecessary to stop the heart during cardiothoracic surgery. There may also be less need for assistance once surgery is under way.

We provide an overview of the evolution of modern surgical robots (based on our modification[1 2] of Camarillo and colleagues[3] and the Rebello[4] classification) applying the SEBMA acronym (Sterotaxic, Endoscopic, Bioinspired, Microbots and Autonomous robots of the future) (Fig. 1). We identify their innovative role in operative healthcare and highlight essentials for the anaesthetist. Are surgical robots as ground-breaking for surgeons as the laryngeal mask airway is for anaesthetists? And what are the likely advancers of this technology for the future?

Prototype robots

The first robots were mechanical machines designed (or programmed) to perform specific human-selected tasks. These included the steam-driven "Flying Pigeon of Archytas" circa 400 BC and the "string-coded" three-wheeled cart of Heron of Alexandria circa 40 AD. Čapek first introduced the word *robot* in 1920 as a Czech term relating to "serf labour",[5] although the term became popularised by Isaac Asimov in the 1940s.[6] Over the next 40 yr, the concept of robotics became increasingly recognised in technological frontiers, receiving a prominent uplift during the Space Race of the 1960s and the Apollo Mission by NASA.[7] Its application in healthcare was commenced through the design of tools specifically geared at achieving a sophisticated level of precision for brain biopsies, where subtle inaccuracies could potentially lead to devastating outcomes. Driller and Neumann[8] reported on such an electromagnetic device in 1967, although the first commercially and clinically available robot designed for a similar task was not available for another two decades. In the interim two main innovative were was taken: first there was a global adoption of mechanical surgical reconstructive devices (anastomotic and haemostatic staplers) that had been present for over a century but had become industrially applied by the Russian military.[9 10] Second, Minimally Invasive Surgery (MIS) which again had been in experimental existence for over a century had become increasingly propagated, as was exemplified by the first laparoscopic cholecystectomy by Mühe in 1985.[11]

First generation – stereotaxic robots

The first surgical robot in clinical practice was the PUMA 200, first utilised in the same year as the first laparoscopic cholecystectomy.[12] This robot was utilised for stereotaxic brain biopsy with the surgeon placing the arms of the robot in a position to perform its task. This device acted as a forerunner to a modified brain tumour excision device known as the Neuromate.[13] Similarly in orthopaedics, robots were introduced to perform procedures that had a clear-cut mathematical and mechanical strategy where tissue tactility and tissue vulnerability had been limited; the predictable geometry of the end-result was of critical importance in the outcome. As a result, devices such as the SCARA robot, the ROBODOC and the AcroBot were introduced[14] to perform these tasks and were initiated from both industrial (IBM) and non-industrial medial sources. At the end of this first era of surgical robotics, several paradigms had been clarified. First, the robotic technology at the time required human surgical review at the end of every step of robotic surgery and robots could not perform multiple sequential tasks on human subjects unsupervised (as the safety concern for tissue damage and life could not be guaranteed). So a master-slave paradigm was introduced where a robot was operating as a direct extension (or "slave" without independent choice) of its surgeon supervisor (this is level 1 autonomy or pure human control according to the US Department of Defence Scale). Second, even the first generation of robotic surgeons had questioned the whole future of robotic surgery[15] in view of its limitations to simplistic and less variable and static tissue platforms (such as the brain and bones). As a result there was a need for increased dexterity and flexibility in operating tissue (soft and more elastic) targets.

Second generation – endoscopic robots

The introduction of the second generation of surgical robots has resulted in the greatest expansion of the concept of robotic surgery to date. This has been as a result of the introduction of soft-tissue surgical capability such as the PROBOT from Imperial College London that can remove pre-defined prostate gland volumes. It is also because of the market-need for highly accurate robotic systems that can augment established MIS surgical technology by building on established stereo-endoscopic platforms such as laparoscopy or thoracoscopy. Here surgical robots could potentially offer four core advantages over traditional MIS surgery by overcoming: (i) difficulty in access to tissue places and organ systems as a result of anatomical restraints such as the pelvis or thoracic cavity causing torque and needing sheer physicality to address, (ii) instruments that lack precision for tasks such as vascular anastomosis that are possible by hand but rendered more complex when performed via the intermediary of a basic MIS instrument as they can require counter-intuitive hand-eye coordination (iii) difficulties in visualisation, which have traditionally been limited to 2-D in MIS; and (iv) lack of tactile or haptic feedback from some tissues whilst operating.

Two of the best-known endoscopic robotic systems were simultaneously developed and introduced just before the millennium. These were The Zeus robotic system (Computer Motion, Goleta, CA, USA) which first became commercially available in 1998, closely followed by the da Vinci robotic system (Intuitive Surgical Inc, Mountain View, CA, USA) in 2000 (Fig. 2).[16] Between 1998–1999 both the da Vinci system and subsequently the Zeus were successfully used in coronary artery surgery as a proof-of-concept operative principle. Furthermore, the Zeus system was applied in Canada to complete the first beating-heart coronary operation, and in 2001 this system was applied to complete the Lindbergh operation; the first trans-Atlantic operation performed by utilising a tele-robotic system where the robotic surgical device (and French surgeons) were in New York and the patient was in Strasbourg in France.[17 18] Market forces led to competition over intellectual property between Computer Motion and Intuitive Surgical Inc, and as a result Intuitive Surgical acquired Computer Motion in 2003, whereupon the da Vinci robot became the only commercially available endoscopic robotic system.

Although other endoscopic robotic platforms have subsequently entered the market, the da Vinci system (Fig. 2) has retained its market dominance. This has been achieved through both its unique market place for several years and its multiple features that allow: (1) a comfortable environment and ergonomic console from which the surgeon can operate remotely from the patient, (2) 3-D imaging that offers accurate depth perception with multiple degrees of magnification, (3) in-line "intuitive" eye-hand control of the instruments at the console, (4) physiological tremor negation, and (5) movement of the mechanical "endo-wrists" with 7 degrees of freedom beyond that of the human wrist during laparoscopy/thoracoscopy with 4 degrees of freedom. This allows the completion of complex microsurgical tasks (one of the da Vinci's predecessors, MIT's Black Falcon[19] offered 8-degrees-of-freedom in articulation to overcome the loss of wrist articulation in laparoscopic/thoracoscopic procedures) (6) Access to "hard-to-reach" areas of the body (such as the pelvis) where traditional open or MIS methods result in excessive torque forces or the requirement for large incisions. This system has also gone through several iterations ranging from the original da Vinci that eventually went from a 3-arm system to a 4-arm system, the da Vinci S with improved vision technology (including 3D HD) and an easier set-up, the da Vinci Si with further visual enhancements and upgradeable architecture, and the da Vinci Xi with enhanced vision and laser targeting in addition to capability for adding future technologies. There are currently just under 4000 da Vinci robot systems worldwide, 66% are in the USA, 17% in Europe, 12.5% in Asia and the remainder at other sites.[20]

The da Vinci device has been used in every organ system to varying degrees. But whilst it had initially been spearheaded as a platform particularly well suited to cardiothoracic surgery, the robot has not been adopted universally for coronary artery surgery[21] as had been anticipated although it has seen adoption in other cardiothoracic pathologies. Rather, it seems particularly favoured in surgery of the pelvis (in urology and gynaecology) where for example, between 2003 and 2010, the national robot-assisted radical prostatectomy (RARP) adoption rate in the USA increased from 0.7% to 42%.[22]

Whilst the da Vinci remains a clear market leader in the robotic surgery market, other second generation robotic platforms exist and include the University of Washington (UW) Raven[23] which is a 6-degree-of-freedom, master-slave system, programmable, modular robot (that has been devised to offer a degree of autonomy in surgery) and the German Aerospace Center's DLR MicroSurge.[24] These platforms share console and utility similarities such that for example, one platform has been utilised to train surgeons for tele-operative experience with one another.[25]

As these second generation platforms are the most widespread and established platforms in current clinical use, they are the platform on to which many novel technological innovations are currently being applied. These range from improved surgical visibility and visual information transfer to improved robot-survival interactions ranging from haptic tactile feedback to ease of application in surgical environments.

Third generation – bioinspired robots

Advances in biomimicry, bionics and autobionics have been evolving in parallel with modern robotics since the 1950s.[26]

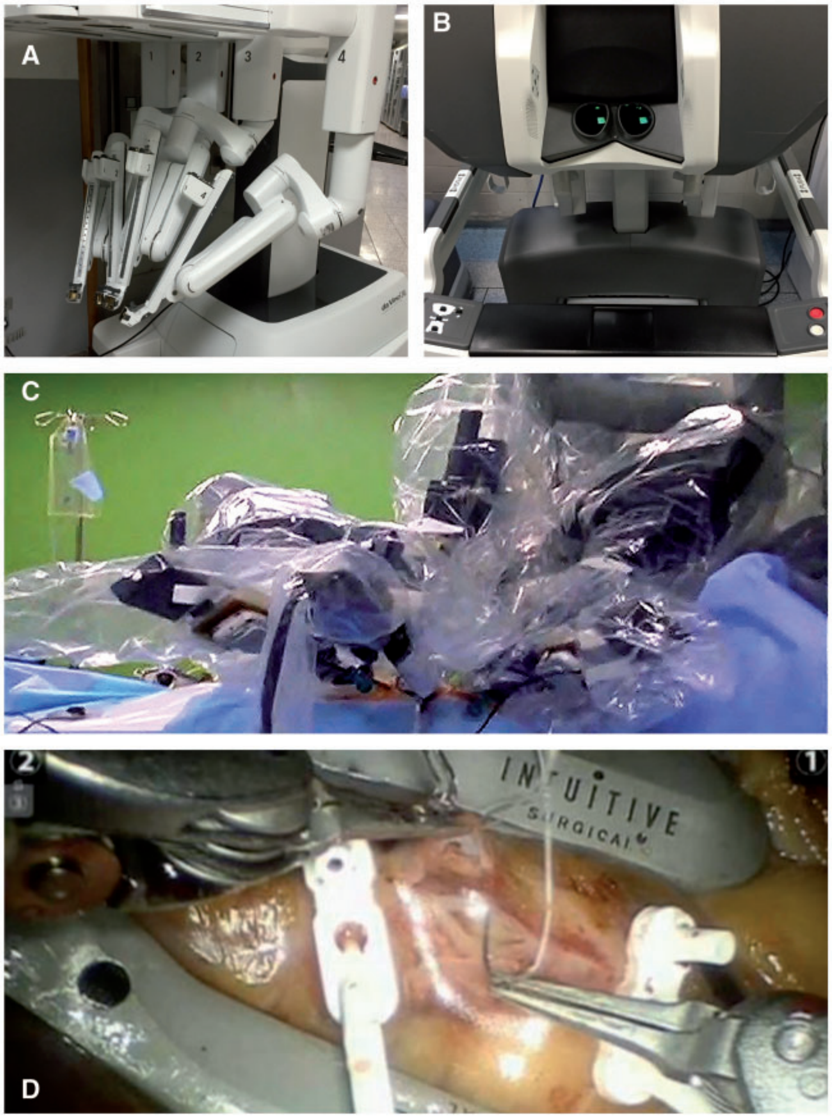

Fig 2 The da Vinci Xi Surgical System (A) robotic arms, (B) console, (C) in the operating environment and (D) performing a coronary anastomosis (courtesy of Dr Leanne Harling).

However, during the development and evolution of second generation robots, MIS and endoscopic methodologies began adopting bioinspired technologies. In endoscopy the NOTES (Natural Orifice Transluminal Endoscopic Surgery) platform developed from a predilection for scarless surgery, whilst MIS surgery wanted to innovate to even less surgical exposure impact, so that multiple MIS ports was transformed into one-port SPL (Single-port laparoscopy). The NOTES technology allowed for surgical tools to be applied at the end of highly articulated snake-like endoscopes, whilst SPL offered a platform for MIS technology to perform surgery with standard laparoscopic/thoracoscopic equipment through enhanced ergonomics that had not previously been available at one site (transabdominal, transumbilical or transluminal). These combined innovations increasingly progressed to the next logical step of producing and utilising MIS instruments with articulated tips to allow MIS surgery to be possible in hard-to-reach areas with minimal access.

The third generation of surgical robots has adopted these principles of biomimicry and multiple articulation technology for multiple surgical pathologies. Most of these robots have been designed in the past decade with a few exceptions (such as Ikuda's microminiature SMA-Shape Memory Alloy[27] servoactuator robot system). Current systems can be classified into (i) Tendon-driven flexible systems such as Imperial College's i-SNAKE and the CardioArm, and (ii) Catheter-navigated systems that have been derived for cardiovascular percutaneous intervention technology. These include mechanical-steering systems such as the Amigo from Catheter Robotics Inc. and the Magellan from Hansen Medical Inc. Catheter systems also include those that have electromagnetic steering such as Niobe from Stereotaxis Inc., the CGCI from Magnetecs Inc. and systems that can offer Magnetic Resonance Imaging (MRI) scanner-guided steering[28] that would allow rapid adoption for the large number of hospitals that have this modality in-house.

As catheter systems are lengthened they can suffer from lack of force of action at distance., This has led to an alternative subgroup of third generation robots utilising concentric tube devices, where this distance effect can be decreased. Both catheter-based and concentric tube systems have been proposed as the next generation in-use robotic system particularly suited to tubular organ groups such as the cardiovascular, neurovascular, urological and respiratory/airway systems in addition to surgical imaging at the microscopic level (imaging foetuses[29] in pregnancy for example) with a miniature "needle-sized" surgical footprint. Concentric robot systems have a particular advantage as they can be very small in size, offer high dexterity, and have the capability to move in highly curved paths.[30] They also have the potential to be reproduced with increased automation through methods such as 3-D printing.[31]

Fourth generation – microbots

The concept of microscopic robots has been present in the public sphere for some time and even gained international prominence from science fiction films such as "Fantastic Voyage" from 1966. Robots at a microscopic level could enter the body with minimal surgical footprint and work as a solitary robot or more likely as a group of robots to image and treat not only conventional surgical diseases but also non-surgical diseases such as infective and immune processes that could be managed at a cellular level. Microbots occupy a millimetre scale (a fraction of a millimetre to several millimetres but larger than the nanometre scale).

Currently capsule endoscopes (such as the PillCam® WCEs-Wireless capsule endoscopes ranging from PillCam® SB3, PillCam® Colon2, PillCam® UGI, and PillCam® PATENCY) are in clinical use, although these function as predominantly imaging modalities that are passively mobile capsules being transported by the peristaltic motility of the gastrointestinal system whilst taking images of the gastrointestinal tract. The next generation of these microbots would include further advances in each component of these robots ranging from vision, locomotion, localisation, telemetry, power, diagnosis and tissue manipulation.[32] Just as in third generation robots, these microbots will benefit from advances in biomimicry where for example locomotion would be based on electromagnetic steering or even autonomous locomotion based on insect-like, fish-like, snake-like or bacteria or parasite-like (flagellate)[33] technology. These systems will have the capability of working with established imaging modalities but can also offer a higher resolution micrometre real-time imaging of diseases and patient anatomy. This is an opportunity to take advantage of imaging systems that allow both electromagnetic navigation and imaging at the same time; these microbots could be integrated with MRI systems[34] (just as in third generation robots), where the scanner will offer external imaging and electromagnetic navigation whilst the microbot(s) will offer internal imaging and disease treatments.

Fifth generation – autonomous systems

Whilst systems since the first generation of surgical robots have been designed to carry a degree of autonomous capacity to perform individual pre-programmed tasks, the concept of fully autonomous, human-level consciousness robots remains predominantly conceptual. Autonomous robots will likely benefit from enhanced machine-learning capability that will require next generation Turing Test intelligence (comparable to human-level intelligence and consciousness).[35 36] They will take the form of the first four generation of robots with added autonomous decision-making capability. These may range from a cyborg humanoid-type platform to a swarm-type system with comparable swarm intelligence.

Obstacles to robotic surgical adoption

Cost

A contemporary da Vinci robotic platform (Fig. 2) costs approximately £1.55 million, with a yearly service charge of £125 000 and instrument cost of approximately £2000 per case. This remains beyond the financing capability of the majority of UK hospitals. Whilst it is clear that robotic surgery costs remain high compared with open and MIS cases,[37 38] there is increasing evidence to suggest the long-term cost efficacy of robotic approaches compared with traditional open operations (such as for radical prostatectomies). This was demonstrated in terms of lower inpatient admissions, hospital bed-days and excess bed-days for robotic surgery that in turn suggest more cost benefit of robotic procedures in the long term. However these effects were non-significant (at 360 days £779 *vs* £1242 and at 1080 days £2122 *vs* £2889).[39] A similar trend has also been reported in European[40] and US private health insurance and the Medicare reimbursement system where long-term (over three years) robot prostatectomy saved $1451 per case. This is largely as a result of lower overall complications, lower incontinence and lower sexual dysfunction costs with a 38–99% probability that robotic prostatectomy provides cost savings according to Monte-Carlo probabilistic sensitivity analysis.[41] A formal Health Technological economic assessment of the cost-effectiveness of laparoscopic and robotic surgery revealed a 10-yr time horizon incremental cost per QALY of<£30 000 for robotic prostatectomy (providing>150 procedures are performed each year). Superiority of robotic outcomes was predominantly because of differences in positive margin rate (which had some limitations on data capture). This identified that with an NHS-type financing system, fixed capital and maintenance charges for the robotic platforms remain core barriers to adoption, although this could be negated to a degree by commercial negotiation and achieving high volumes of cases in each centre (more than 100–150 annual cases).[42]

There remain a handful of companies with one dominant market leader offering these robotics platforms, predominantly of the second generation. One method of overcoming these cost effects is to increase market completion by a concerted effort of clinicians, robot scientists and policy-makers supporting new entrants to the market. Additionally, the wider adoption of these devices based on appropriate evidence may also offer improved cost schemes to allow their utilisation. This may be coupled to enhanced economic strategies such as institutional sharing of devices and costs to ensure easier access and financing for robotic surgery in a wider patient population.

Learning curve

One of the core advantages of robotic surgery has been its "promise" to offer a shorter learning curve when compared with MIS platforms as a result of its "intuitive" technical adoption. This has been demonstrated in some studies,[43] though there is no large scale randomized evidence to support this finding at this time. Limitations for this evidence suggest that in the current era, most practising surgeons almost universally become familiarized with MIS techniques before they go on to practice robotic surgery, so that a true comparison of their learning curves could be biased in this setting. Additionally, one systematic review of the literature has identified that the measurement of MIS learning curves remains multifaceted and ill-defined in the majority of studies, with only a handful of analyses utilizing the recognized CUSUM model of assessing trends in multiple surgical outcomes within a clinical setting.[44] Future work will need to offer increased robustness in data comparability between robotic and MIS learning curves if this factor is to be used as a source to decide on the platform utilized in a particular clinical setting.

Learning curves to achieve surgical proficiency with robotic platforms differ widely between procedures, pathologies and anatomical sites (just as in in open and MIS procedures). As a result, comparing learning curves and proficiency rates between procedures and techniques can be problematic as utilizing open, MIS and robotic procedures to achieve the same end result may not follow the same steps and therefore are difficult to compare clinically and statistically. It has been suggested that the technical advantages of robotic surgery, which reduce the cognitive and physical demands of minimally invasive surgery, would ameliorate the challenging surgical learning curve. This would allow surgeons, including those without previous laparoscopic experience, to provide the benefits of minimally invasive surgery to their patients. However, the evidence to support these assertions is limited and there is a paucity of comparative data. Utilising an example of robot-assisted laparoscopic radical prostatectomy (RALP), sources identify a learning curve that ranges between 12 and 250 cases based on the definition of "learning curve" utilised.[45] It typically takes 150–250 cases to achieve the learning curve for operative time, though the learning curve for oncological and biochemical outcomes in this case lies at approximately 750 cases.[46]

Operational and environmental limitations

Most current robotic platforms carry multiple operational challenges for day-to-day application. These include (i) sufficient theatre space that can accommodate the large dimensions of current devices, (ii) theatre staff (not only surgeons and anaesthetists) that are familiar with the robotic platform set-up, (iii) managing the complex ergonomics of a busy theatre space with a robotic device *in-situ* and (iv) the ability to minimise robotic operating room turnover time. Attempts at managing the latter point derive from the application of "pit-stop" models originally practised in the motor racing industry for rapid but exact changeovers within a surgical environment. This includes the use of multiple anaesthetic teams and anaesthetic rooms.[47] Addressing the former points however will increasingly rely on adoption of the next generation of robots with a smaller surgical footprint to allow increased ease of use and accessibility to these devices. Smaller devices would also offer ease of transport which in turn could increase the possibility of sharing devices as part of a business model, or ease of transporting devices to manufacturers for repairs and updates.

Ancillary Equipment and intellectual property

MIS operations remain highly dependent on ancillary equipment such as stapling guns, scissors and haemostatic devices. Whilst in MIS many of these devices simply need to function within the constraint of available port sizes, the nature of telerobotic surgery not directly in proximity to the patient, limits the number of devices available on the robotic platforms. Two processes are underway to overcome this issue: (i) the robotic companies are designing and implementing their own devices to accommodate surgical need (for example the da Vinci Xi EndoWrist Stapler 30 Instruments And Reloads), that can be expensive for the robotic company who are not traditionally designers of MIS equipment; and (ii) device companies can design instruments that can work on the robotic platforms. However this also has barriers regarding the ownership of device intellectual property and its transfer between device companies and robotic companies, and carries cost considerations that would affect healthcare institutions and their patients. One possible solution lies within the academic sector where surgeons and engineers can attempt to design and solve robotic surgical needs at an equitable price.

Overview of clinical outcomes and current evidence

Robotic surgery has been described by some as the natural evolution to laparoscopic surgery along the minimally invasive continuum.[48] Essentially offering similar advantages in reducing the systemic inflammatory and metabolic insult whilst providing improved precision and accuracy in surgical technique because of superior 3 D dexterity and it offers potential in future developments including digitally enhanced analysis of tissues with integrated immunofluorescence and improved outcomes in benign and malignant disease.[49]

Current robotic surgical evidence points towards a convincing reduction in postoperative surgical and non-surgical complications, reduced blood loss, improved recovery rates, improved cosmesis and reduced length of stay in comparison with open surgery.[50–52] The comparison with MIS however is equivocal, although several studies do show some advantages in length of stay, conversion rate and estimated blood loss.[53–55]

Concerns regarding robotic surgery predominantly focus on increased length of operating time (and cost), although gains in improved recovery times and benefits of robotic techniques in more complex surgery and with specialist groups may go some way to counter this. One area of particular superiority in comparison to MIS is that of a reduced conversion to open surgical technique, which has particular benefit in obese and elderly patient groups.[56]

There is evidence from a variety of robotic surgical specialities that in comparison to the non-obese population there is no increase in intraoperative or postoperative complications, conversion to laparotomy or operative time in obese patients.[57–59] In fact in some specialities they have demonstrated a shorter operative time in obese patients using robotic surgery in comparison with open surgery,[60] and in comparison with laparoscopic surgery it has been shown that return of bowel function and discharge home is faster by 24 h, with otherwise comparable operative time, blood loss, conversion rates, resection margins and complications.[61] However, robotic procedures do not universally demonstrate speedier results, such that increased operative times and length of stay has been reported when using robotic *vs* laparoscopic techniques in bariatric surgery.[61]

Outcomes in the elderly have been shown to be better after robotic surgery in comparison with open surgery, with reduced surgical and medical complications, improved length of stay and quicker discharge home. This may be as a result of reduced blood loss and transfusion rates, alongside reduced wound

Table 1 Perioperative considerations for robotic surgery

Perioperative Stage	Considerations	Rationale
Preoperative	Environmental considerations and ergonomics – may benefit from visiting other departments if new to robotics	Need space and ergonomic layout for table, robot, surgical, anaesthetic and nursing teams for safe and efficient care[49 69]
	Multi-disciplinary team training – consider simulation	Robot set up and patient positioning takes time and experience but can be efficient. Critical incidents (cardiac arrest for example) require special consideration[49 69]
	Preoperative assessment and multi-disciplinary decision-making regarding benefits and risks of robotic surgery and anaesthetic technique	More high risk patients are considered for minimally invasive surgery and robotic surgery has particular physiological impact
Induction	Induce on theatre table	Avoids transfer and can increase efficiency
	Consider second anaesthetic team to anaesthetise further patients	Minimize turnover time and improve robot utilisation efficiency
	Consider opioid based neuroaxial block	Evidence base for improved pain management[70 71]
	Positioning of lines in most accessible position/away from robot	Improved ergonomics and access, reducing complications
	Invasive lines only in high risk patients	Routine cases may be managed without invasive monitoring
	Trial of positioning in high risk patients	Ensure patient can tolerate Trendelenburg positioning before robot docking
	Nasogastric tube not always required	Regurgitation may be absent in short low-risk cases
Maintenance	Close attention to positioning and padding – gamgee for arms, inflated gloves to protect hands. Lacrilube to eyes, eyes further padded and taped with tegaderm, with regular checks	Complications because of peripheral nerve injury, lower limb compartment syndromes, oedema and ocular compromise[72 73]
	Shoulder supports and horizontal bar to protect face from robot arm	Protection of patient from moving and from robot arm movement
	Consider TIVA approach	Potential benefits for cancer management[74]
	Maintain muscle paralysis (may not be required with remifentanil infusion)	Movement may cause significant patient injury once robot docked
	Restrictive fluid management where possible	Avoid complications of oedema
	Use of mobile phone app spirit level to measure degree of Trendelenburg	Achieve accurate angle of Trendelenburg
Emergence	Consider degree of oedema	Particular issue in prolonged steep head down surgery
	Cuff leak check, consider airway exchange catheter	
	Consider overnight intubation and dexamethasone in high risk cases	Aim to avoid difficult emergency re-intubation[72]
Postoperative	Enhanced recovery principles	Consolidate benefits of minimally invasive surgery and ensure optimal outcomes particularly for high risk or frail patients
	Post anaesthetic care unit/critical care for high-risk patients	

and fascial complications despite longer operating times.[62] Interestingly several studies across a variety of surgical specialities have found there to be no differences in outcomes between younger and older patient groups having robotic surgery,[63–65] indicating age alone is not a risk factor. One study demonstrated that older patients having robotic surgery *vs* younger patients having open surgery had significantly lower early complication rates (17% *vs* 59%).[52]

In terms of specialist surgeries, the benefits of robotic techniques have enabled increasingly complex procedures such as retroperitoneal lymph node clearance for treating testicular cancer. Using an open approach would be extremely invasive, but using a robotic approach there is potential for a return to full physical fitness within three weeks.[66] These are important considerations in terms of improving outcomes in cancer management and patient satisfaction and quality of care; these are outcome markers that can demonstrate the incremental gains offered by robotic surgery.

We performed a systematic review[67] of all the papers in the literature for the first 30 yr of robotic surgery (1985–2015). Assessing all available data-sets, we identified 108 studies on 14 448 patients. Those reporting on robotic *vs* open surgery (OS) included 11 RCTs and 39 prospective studies, which together demonstrated lower blood loss at 50.5%, lower transfusion rate at 27.2%, lower length of hospital stay at 69.5%, and reduction of 30-day overall complication rate at 63.7% in favour of robotic surgery when compared with open surgery. For robotic *vs* MIS, there were 21 RCTs and 37 prospective studies, which demonstrated mildly reduced blood loss at 85.3% and transfusion rate at 62.1% in favour of robotic surgery but similar length of hospital stay (98.2%) and 30-day overall complication rate (98.8%) when robotic surgery was compared with MIS. In both comparisons, robotic surgery prolonged operative time (7.3% longer than open surgery and 13.5% longer than MIS). In our analysis, for the first 30 yr, there were relatively few RCTs, and those that were present suffered from inadequate statistical power and a high risk of bias. As a result, there has been a recent communal effort to produce high quality randomized data on robotic outcomes. For example the recent[68] Australian randomised controlled phase 3 study comparing robot-assisted laparoscopic prostatectomy and open radical retropubic prostatectomy, revealed that at 12 weeks, there was no significant difference in standard oncological or quality of life outcomes. Studies such as this (which was the first such RCT in prostatectomy surgery), with much longer outcome data (years rather than weeks) will help clarify the decision-making in robotic surgery for the future. Lastly, the notable lack of evidence for robotic procedures requires the development of validated robot-specific methodological tools to assess and evaluate this evolving technology. This includes methodologies to appraise well-defined clinical endpoints including specific quality of life (QoL) and patient reported outcome measures (PROMS) combined with robust cost-efficacy and economic analyses.

Anaesthetic perspectives

Whilst all care providers consider the patients' surgical journey through the treatment pathway by appraising whether the advances made by robotic surgery demonstrate benefits in terms of outcomes and whether these outweigh associated risks, anaesthetists also consider several core anaesthetic-specific factors as a part of patient management (Table 1).

The anaesthetic risks associated with robotic surgery are largely associated with length of operating time and positioning.[72] The most frequent complications are peripheral neuropathies, corneal abrasions, vascular complications including compartment syndrome, rhabdomyolysis and thromboembolic disease, and the effects of oedema (most significantly cerebral, ocular and airway), which are elegantly described in a recent review.[72] Additionally, obesity is widely accepted as increasing the risk of perioperative complications in robotic surgery. Robotic prostatectomy is considered to be the index operation and studies in obese patients undergoing robotic-assisted radical prostatectomy (RARP) show higher complication rates compared with non-obese individuals, such that in some cases the robotic approach fails to decrease the risks of obesity-associated surgical complications.[75] Together these complications form the basis for the anaesthetic technique.

As the learning curve for robotic surgery has progressed from both a surgical and anaesthetic perspective, a reduction in surgical time and perceived requirement for invasive lines has been observed. However as confidence grows, more complex surgeries and patients with increasing comorbidities will be considered for surgery, highlighting the need for thorough preoperative assessment, multidisciplinary decision-making and assessment on a case-by-case basis.

Robotic surgery has been utilised in a range of specialities including urology, gynaecology, cardiac, thoracic, upper and lower gastrointestinal and endocrine surgery. Anaesthetic approaches for each procedure will be unique. However, similar considerations will be based around patient positioning, the physiological impact of surgery, and potential patient safety issues including the limitations of restricted patient access. On an organisation level teamwork and communication between anaesthetic staff, surgical staff and nursing teams is imperative in terms of robotic setup, and docking and undocking, particularly in the event of an emergency such as cardiac arrest.[49] Simulation has been recommended to improve efficiency in these circumstances.[69]

The required position for many types of robotic procedures is the steep Trendelenburg.[76–78] The respiratory and cardiovascular implications of this extreme and exaggerated position have been well described.[49 69 76–78] However, in the majority of patients, including those with chronic respiratory disease and morbid obesity, this can be managed with protective pressure control ventilatory strategies including positive end-expiratory pressure and optimal fluid management, plus invasive lines and vasopressor support in the high-risk patient. Furthermore, a potential technique in counselled high-risk morbidly obese patients is to use steep Trendelenburg in the anaesthetic room after induction of anaesthesia and tracheal intubation to monitor respiratory and cardiovascular effects. If significantly compromised in this position, surgery may be conducted as an open procedure, or postponed for further discussion and decision-making. Patients are fully consented for this before induction. Awaited are the results of a current study looking at ventilatory strategy and pulmonary outcomes in robotic surgery (AVATaR), a collaboration between groups in Brazil, Italy, Holland and Germany (clinicaltrials.gov number NCT02989415).

Limited access to the patient once docked, the precarious positioning of the patient, and the absolute need for no movement intraoperatively raises several challenges for the anaesthetist. Care and attention to positioning and padding is one of the most crucial elements. There is some evidence that there is a slightly higher incidence of peripheral nerve injury in the upper and lower limbs for robotic surgery *vs* laparoscopic surgery, and whilst in many cases this resolves in under six weeks, it may persist for more than six months.[72] Shoulder braces and beanbags have been specifically implicated in brachial plexus injuries and so should be avoided.[79] Some centres advocate chest banding to stabilise position, but this may compromise lung compliance.[49] Compartment syndrome and rhabdomyolysis are rare but significant consequence of positioning, long procedures and tight leg braces.[53] Attention needs to be paid to ensure straps do not compromise blood supply, and additionally that systemic cardiovascular integrity is maintained. Gluteal compartment syndrome is a specific risk, which although rare[80 81] has significant consequences and so gluteal cushioning is recommended.[82] Additional large bore access with a long venous line connection and muscle paralysis (in the form of neuromuscular blocking agents or a remifentanil infusion) would also be advised. High postoperative vigilance for complications and appropriate management protocols optimise outcome and patient satisfaction.

After patient safety is considered, the aim for anaesthesia is to contribute to the incremental gains offered by robotic surgery by providing optimal fluid management, analgesia, reducing postoperative nausea and vomiting (PONV) and cognitive dysfunction, improving recovery and discharge times and overall patient satisfaction. With a newly realised opportunity to contribute to overall cancer outcomes with evidence suggesting the superiority of total i.v. anaesthesia (TIVA) over volatile anaesthetic techniques,[74] it seems sensible to consider the use of TIVA in robotic procedures for oncological surgery. Despite the advantages of TIVA in terms of PONV and recovery times, there currently remains limited evidence to make recommendations for its use in all types of robotic surgery.[83] Postoperative analgesia may be improved with neuroaxial techniques such as intrathecal opioids as reduced systemic opiate use, reduced pain scores and increased patient and nursing staff satisfaction have been demonstrated with this approach.[70 71]

Oedema can become problematic, particularly in dependent areas after long surgeries in the steep head down position. Laryngeal oedema may occur, and presents as respiratory distress and airway compromise in the immediate postoperative period. The overall incidence of reintubation after robotic surgery is around 0.7%, and delayed extubation 3.5%; but the incidence of airway oedema may be up to 26%.[72] Many anaesthetists perform direct laryngoscopy and use a leak test before extubation;[84] some centres also use airway catheters in case of the need for re-intubation. Facial and periorbital oedema can be indicative of laryngeal oedema, and be implicated in other problems such as corneal abrasions, as oedema may cause eyelids to separate. Vigilance, careful lubrication, taping, padding, and positioning of drapes is advised, and consideration to inserting a nasogastric tube to prevent gastric content contamination. The increase in intraocular pressure intraoperatively has also meant that glaucoma can be considered as a relative contraindication to some forms of robotic surgery. Visual loss is rare, but has been described in association with posterior ischaemic optic neuropathy.[85–87] Cerebral oedema can also be a significant complication causing confusion or reduced levels of consciousness postoperatively. The pathogenesis is likely because of increased venous pressure in the Trendelenburg position with pneumoperitoneum leading to increased intracranial pressure and capillary leak. Preventative strategies include limiting operative time, minimising the angle of Trendelenburg, limiting insufflation pressure to 8 mm Hg where possible, and fluid restriction.[88] It is also advisable to maintain a normal end-tidal carbon dioxide concentration. High-risk patients can be kept intubated for a period of time postoperatively. Despite a potential delay to extubation, the recovery and discharge from ITU and overall hospital stay can remain lower than that after open surgery. It is clear that a fluid restriction strategy may help to reduce complications in association with oedema, but this obviously needs to be balanced against compromise to the cardiovascular and renal systems.[69]

As the experience with robotic technology has expanded for surgeons, the anaesthetic considerations for avoiding potential hazards have become better understood and realised, as have the postoperative benefits of the robotic technique. However, there remain many unresolved questions. More multidisciplinary considerations and evidence to support the benefits of different surgico-anaesthetic approaches for individual cases should be investigated. Overall we need to aim towards conclusive evidence as to which anaesthetic and analgesic approach offers the most postoperative benefits to patients. We should be able to justify the cost of interventions in terms of patient benefits from a physiological impact, pathological outcome and quality satisfaction perspective, which will also ensure that multidisciplinary teams and patients can make fully informed decisions and choices, particularly those in high-risk categories.

The future of robotic surgery

The future of robotic surgery hinges on five core TECAT dimensions: (i) *Technology*, continual application of advancing and next generation technologies to offer improved surgical precision in a wider range of cases with increased usability to achieve better clinical outcomes, (ii) *Evidence*, increased evidence to select the best robotic platforms for the most appropriate population-base, (iii) *Cost*, cost-efficacy for individuals, institutions and nations to afford robotic surgical healthcare (iv) *Awareness*, increased societal and patient awareness and comfort in having surgical procedures performed when appropriate, and finally (v) *Training*, enhanced training of surgical, anaesthetic and associated healthcare staff to have increased familiarity and improved team outcomes when applying surgical robotics. Whilst we have already highlighted some of these factors in the text, this section will focus on future technologies that can enhance the next generation of robotic procedures.

Visualization

Dynamic View Expansion or Mosaicing have already been introduced in MIS and can offer robotic platforms a wider field of view than standard MIS camera technology.[89 90] Whilst multimodal visualisation technology is already being applied in robotic procedures, such as augmented reality (overlaying of CT, MRI, ultrasound or other imaging) to guide intraoperative decisions, these techniques continue to need enhancement by improved depth perception with inverse realism, and to offer see-through vision of an embedded virtual object while sustaining the vision of standard operative anatomical landmarks.[91]

Real-time intraoperative ultrasound (USS) had added a technically simple yet diagnostically powerful imaging modality to robotic surgery and is used extensively for robotic partial nephrectomy. It has potential in prostatectomy and other procedures where it can help differentiate tissues based on their echogenicity.[92 93] A predominance of 3-D systems with smaller sized cameras at 4 mm (such as the Visionsense VSiii) and smaller will offer stereoscopy with increased use of other ports for surgery. Tissue imaging with photodynamic capture and enhanced microscopy ranging from Narrow Band Imaging (NBI), Fluorescence Lifetime Imaging (FLIM), Optical coherence tomography and Flexible Confocal Microscopy (FCM)[94–96] will offer increased real-time visual histological data that can identify tumour cells and margins. Robotic cameras can emit and quantify tissue autofluorescence of reflectance spectra to highlight any microscopic surgical pathology for resection. This coupled with enhanced diagnostic computation, neuromorphic visual processing tools and machine-learning algorithms[97] will allow imaging at a number of tissue scales (including molecules, cells tissues and organs)[98 99] through a new generation of real-time disease diagnostic capability well beyond that of traditional assessment tools.

Somatosensory perception and beyond

Operating with a refined sense of touch to assess bodily tissues can be of critical importance in differentiating pathology and making on-table surgical decisions. This has been largely lacking or exists at a blunted level in current MIS systems, although this has not necessarily been associated with poor results.[100] Nevertheless, increased tactility will offer a new level of tissue perception for robotic surgeons that could be translated into increased precision and safety. Increased understanding of the neurophysiology and mechano-transduction of tactile perception through vibrotactile cueing[101] and traction loads are allowing the next generation of wearable haptic systems for robotic platforms offering tactile enhancement.[102 103] This increased tactility will allow surgery through ever smaller operative utensils with advanced kinematics and higher degree-of-freedom joint capacity.[104]

Every element of the operative environment can now contribute to robot surgical decision-making. One prominent novel example is Imperial College's intelligent scalpel or i-Knife which can utilise diathermy smoke to offer pathological diagnoses (for example cancer *vs* non-cancerous tissue) based on the metabolic profile of the tissues being diathermied.[105]

Robot-surgeon interactions

Many novel robotic technologies focus on offering technology to enhance surgical decisions, where the surgeon is the hub and information can be given to the surgeon who then processes this to formulate a conscious plan which in turn is executed manually into an operative manoeuvre. Increasingly an additional approach has been generated where the robot can also pick up information from the surgeon to support surgical decisions in parallel as a "supportive partner".

For example, neural integration is being developed to allow robots to derive information from their surgeon thorough EEGs, magnetic EEGs and near infra-red spectroscopy (NIRS), so that it may (i) utilise machine learning algorithms to help record the steps of an operation and (ii) possibly offer a modification of the surgical environment to optimise surgical precision, accuracy and safety.

Video-oculography (eye-tracking) is a non-invasive technology that can be utilised to assess regional brain activity[106] through optical topography (OT) and gaze-behaviour, to better understand surgeon behaviour and decision-making which in turn can be applied to enhance the next generation of surgical trainees. Additionally, gaze-contingent information can also offer the assessment of saccadic eye movements and ocular vergence to enable an understanding of surgeon 3 D depth perception through wearable eye-trackers. This also allows a deeper appreciation of real-time surgical behaviour and decision-making that can help augment training and improve surgical safety.[107] However it also carries a novel value of "feeding-back" modified visual information through a tele-robotic module to allow a surgeon to overcome operative environmental complexities. For example, gaze-contingency information can be used to overcome the difficulties of operating on a beating heart in off-pump cardiac surgery, by generating a non-moving "phantom heart" image so as to enable the surgeon to visualise a still heart for performing surgery.[108]

Conclusions

Robotic surgery applies actuators and computer control into all surgical specialties with an overarching aim to combine a minimally invasive approach with improved surgical precision and accuracy. The healthcare sector's "learning curve" for robotic technologies has so far met with some challenge and resistance including pertinent concerns towards cost and lack of evidence.However the benefits in terms of postoperative recovery and advantages in particular patient groups are becoming increasingly realised in selective procedures and cases. Future promises towards the integration of current robotic systems with advanced real-time anatomical and immunohistological imaging technologies, alongside more discrete and manoeuvrable instruments with improved visualisation and tactile feedback, offer exciting surgical opportunities. These opportunities have the potential to translate into improved clinical outcomes in terms of cancer survival and overall quality of care for a wide range of complex and high-risk patients. These procedures have the potential to offer improvements in stronger measures of outcome evidence such as quality of life, cost-efficiency and patient reported outcome measures (PROMS).

In its current form, robotic surgery continues to have the potential to become dramatically transformative in global healthcare, although it has not achieved this accolade yet. The future of this field includes exposure to continual innovation in technology, but also costing strategies and healthcare value networks, to allow the next generation of robotic platforms to gain establishment in the modern healthcare market. This also requires training and adoption of evidence-based robotic approaches and gaining experience and confidence in the skills necessary for managing the complexities and complications of patients undergoing robotic surgery. These skills need to be included within the anaesthetic and surgical training curricula, which can be enhanced within the simulation environment. These factors all require underpinning with the highest levels of evidence to develop the optimum multi-disciplinary approaches to integrate surgical, anaesthetic and allied specialties to deliver robotic surgery into its next stage of innovative evolution.

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Authors' contributions

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Study conduct: all authors
Data analysis: all authors
Writing paper: all authors
Revising paper: all authors

Declaration of interest

None declared.

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